The Araucaria Project. Determination of the LMC Distance from Late-Type Eclipsing Binary Systems: I. OGLE-051019.64-685812.3 [1]

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ABSTRACT

We have analyzed the double-lined eclipsing binary system OGLE-051019.64-685812.3 in the LMC which consists of two G4 giant components with very similar effective temperatures. A detailed analysis of the OGLE I-band light curve of the system, radial velocity curves for both components derived from high-resolution spectra, and near-infrared magnitudes of the binary system measured outside the eclipses has allowed us to obtain an accurate orbit solution for this eclipsing binary, and its fundamental physical parameters. Using a surface brightness-(V-K) color relation for giant stars we have calculated the distance to the system and obtain a true distance modulus of 18.50 mag, with an estimated total uncertainty of $\pm$ 3%. More similar eclipsing binary systems in the LMC which we have discovered and for which we are currently obtaining the relevant data will allow us to better check on the systematics of the method and eventually provide a distance determination to the LMC accurate to 1 percent, so much needed for the calibration of the distance scale.

Subject headings: distance scale - galaxies: distances and redshifts - galaxies: individual(LMC) - stars: eclipsing binaries

1. Introduction

An accurate calibration of the extragalactic distance scale is one of the most important and challenging tasks of modern astronomy. In spite of substantial improvements achieved over the years in this field there are still important systematic errors associated with both the primary Cepheid and other secondary methods which do not yet allow to obtain extragalactic distances, and thus the Hubble constant with the high accuracy needed for cosmological applications. The major uncertainties in the use of Cepheid variables as standard candles continue to be our lack of a detailed understanding of the effect of metallicity on the Period-Luminosity (PL) relation (e.g. Romaniello et al. 2008; Groenewegen 2008: Gieren et al. 2005; Storm et al. 2004) and, perhaps most importantly, the distance to the LMC. The LMC provides the fiducial Cepheid PL relation, extremely well established from the OGLE microlensing survey in optical bands (Udalski et al. 1999a; Soszynski et al. 2008), and by the work of Persson et al. (2004) in the near-IR JHK bands. The distance to the LMC is likely to constitute the largest source of uncertainty in the construction of the extragalactic distance ladder with the Cepheid method (Freedman et al. 2001). In our ongoing Araucaria project, we are addressing these issues in an effort to reduce the current systematic uncertainties in both the metallicity effect on the Cepheid PL relation and the distance to the LMC.

Detached eclipsing doubled-lined spectroscopic binaries offer a unique opportunity to directly measure accurate stellar parameters like mass, luminosity, radius (Andersen 1991), and distance (Paczynski 1997). It has been argued (Paczynski 1997; Paczynski 2000) that with current observational facilities, eclipsing binaries carry the potential to yield the most direct (one step) and accurate (about 2-3%) distance to the LMC. For an extensive historical review of this technique the reader is referred to the paper of Kruszewski and Semeniuk (1999), while the method itself is very well described by Lacy (1977), and Paczynski (1997). Briefly, using high-quality radial velocity and photometric observations, standard fitting routines (e.g. Wilson and Devinney 1971) provide very accurate masses, sizes, and surface brightness ratios for the components of a double-lined eclipsing binary (e.g. Andersen 1991). The distance to the system follows from the dimensions determined this way, plus the absolute surface brightness, which can be inferred from the observed stellar colors from a precise

[1]Based on observations obtained with the ESO NTT for Programmes 074.D-0318(B) and 074.D-0505(B), and with the Magellan Clay telescope at Las Campanas Observatory

empirical surface brightness-color calibration. Such relations, for different colors, are well established for stars with spectral types later than A5 from accurate measurements of stellar angular diameters by interferometry (di Benedetto 1998; Kervella et al. 2004, Groenewegen 2004, di Benedetto 2005).

This powerful technique has been used by Thompson et al. (2001) to determine the distance to ω Centauri using observations of the cluster eclipsing binary OGLEGC17. Unfortunately, late-type main sequence binary stars located in the LMC are too faint to secure high resolution spectra for accurate radial velocity measurements even with the largest current telescopes. Therefore the few attempts made to use eclipsing binaries to determine the distance to the LMC (e.g. Guinan et al. 1998) have used relatively bright early-type systems, for which however an accurate empirical surface brightness – color relation is currently not available. As a consequence, theoretical models have to be employed in this work, this has prevented the full realization of the potential offered by eclipsing binaries for an accurate measurement of the distance to the LMC.

In order to improve on this situation our group has performed a careful analysis of the optical (BVI) light curves of the LMC eclipsing binary stars catalogued by the OGLE consortium (Wyrzykowski et al. 2003). We have used the Wilson-Devinney (WD) code to identify eight long-period eclipsing systems composed of *two late-type giant components*. These systems offer for the first time the opportunity to take full advantage of the eclipsing binary method and measure a truly accurate distance to the LMC, using the empirical surface brightness – color relation which is very well established for late-type stars. During the past two years we have been obtaining near-infrared and high-resolution spectroscopic observations for all these systems. In this paper, we present the first distance measurement to the LMC based on our to-date best observed late-type eclipsing binary system, OGLE-051019.64-685812.3.

2. Observations, Data Reduction and Calibration

2.1. Optical Photometry

The optical photometry of our binary system was obtained with the Warsaw 1.3m telescope at Las Campanas Observatory in the course of the second and third phases of the OGLE project (Wyrzykowski et al. 1999). A total of 780 I-band epochs spanning a period of 4124 days were secured. In order to obtain accurate colors, we also collected 75 V-band band images. The data were reduced with the image-subtraction technique (Udalski 2003, Wozniak 2000). The instrumental data were very carefully calibrated onto the standard

system using observations of several Landolt fields over many dozens of photometric nights. The estimated zero point errors are about 0.01 mag in all bands (Udalski et al. 1999b). For more details about the instrumental system, observing, reduction and calibration procedures adopted in the course of the OGLE project the reader is referred to the references cited above.

2.2. Near-Infrared Photometry

The near-infrared data presented in this paper were collected with the ESO NTT telescope on La Silla, equipped with the SOFI infrared camera. We used the Large Field setup with a field of view of 4.9 x 4.9 arcmin at a scale of 0.288 arcsec/pixel. The gain and readout noise were 5.4 e/ADU and 0.4 e, respectively. The data were obtained in two observational programs, 074.D-0318(B), 074.D-0505(B) (PI: Pietrzyński) as part of the Araucaria Project. Single deep J-band and K_s-band observations of our target field were obtained under excellent seeing conditions during five different nights. On these nights, we also observed a large number (8-12) of photometric standard stars from the UKIRT system (Hawarden et al. 2001) at a variety of airmasses and spanning a broad range in colors.

To account for the frequent sky level variations in the infrared spectral region, especially in the K_s-band, the observations were performed with a dithering technique. For the K_s and J-band observations we averaged over 10 consecutive 10 second integrations (DITs) at any given pointing before moving the telescope to a randomly selected different position within a 25×25 arcsec square. Between 15 and 25 such dithering positions were obtained through the K_s-band. In the case of the J-band filter this number varied from 11 to 15.

The reductions were performed in a similar manner to those described in Pietrzyński and Gieren (2002). The sky was subtracted from the images with a two-step process implying masking of the stars with the xdimsum IRAF package. Then the individual images for each field and filter were flatfielded and stacked into a final composite image. The PSF photometry was carried out with the DAOPHOT and ALLSTAR programs. About 20-30 relatively bright and isolated stars were selected visually and the first PSF model was derived from them. Following Pietrzyński, Gieren and Udalski (2002), we then iteratively improved the PSF model by subtracting all stars from their neighbourhood and re-calculating the PSF model. After three such iterations no further improvement was noted, and the corresponding PSF model was adopted.

In order to convert our PSF photometry to the aperture system, aperture corrections were derived for each frame. This was done by using the previously identified candidates for PSF calculations after removing all nearby stars that could contaminate our photometry.

The median from the aperture corrections derived for these stars was adopted as a aperture correction for a given frame. Typically, the rms scatter in the aperture corrections derived in this way was better than 0.01 mag.

Aperture photometry on the standard stars was performed by choosing an aperture radius of 16 pixels. Four of our five nights were photometric and the tranformations onto the UKIRT system were performed independently for each of them. The total error of the zero points of the K_s and J magnitudes is estimated to be about 0.02 mag for any given night.

2.3. High Resolution Spectroscopy

Echelle spectra were collected with the Magellan Clay 6.5 m telescope equipped with the MIKE spectrograph. A single 5 x 0.7 arcsec slit was used during the observations giving a resolution of about 40 000. A total of 11 spectra with net exposure times of 1 hour each were collected. In order to allow for better cosmic ray removal each observation was divided into two consecutive 0.5 hour exposures. The spectra were reduced with the pipeline software developed by Daniel Kelson, following Kelson (2003). The resulting S/N ratio was about 10 at a wavelenght of 4500 Å. Radial velocities were measured with the TODCOR package (Mazeh and Zucker 1994) in the wavelength regions 4125 - 4320, 4350 - 4600, and 4600 - 4850 Åusing templates taken from the Coelho et al. (2005) synthetic library. The final radial velocity for a given spectrum was adopted as the mean from the measurements obtained from the different wavelength ranges. The individual RV measurements are listed in Table 1.

3. Spectroscopic and Photometric Solutions

The following final ephemeris was derived from the photometric data for our binary system based on the AoV technique (Schwarzenberg-Czerny 1996):

$$\mathrm{P} = 214.370 \pm 0.008\, days \qquad \mathrm{T}_0 = 2450498.0 \pm 0.1 \text{ days}$$

We adopt the photometric ephemeris and derive the systemic velocity, the velocity amplitudes, eccentricity, periastron passage, and the mass ratio from a least squares fit to the velocity data (see Fig. 1 and Table 3). The measured systemic velocity confirms that our binary star belongs to the LMC.

The mean (constant) V (16.655 mag), I (15.685 mag), and K (14.437 mag) band magnitudes of the system outside eclipse were derived as the average of all of the individual out-of-eclipse observations obtained in the corresponding band. A reddening of E(B-V) = 0.146 ± 0.02 mag was adopted for the binary from the OGLE extinction maps (Udalski et al. 1999b).

Figure 2 shows that the observed minima have approximately the same depths, indicating that the effective temperatures of the components must be similar. Therefore we can assume that the difference in brightness is caused by the difference in the temperatures and taking the effective temperature of the whole system as derived from the observed colors, and using several independent empirical calibrations (see Table 2), calculate the effective temperatures of the individual components. Effective temperatures of $T_1 = 5300 \pm 100K$ and $T_2 = 5450 \pm 100K$, were obtained in this way for the primary and secondary components, respectively. Next, the limb darkening coefficients corresponding to the logarithmic formula were taken from the tables of van Hamme (1993) by assuming a metallicity of [Fe/H] = -0.5 dex (e.g. the typical metallicity for the red giant stars in the LMC; Olszewski et al. 1991, Cole et al. 2000), and adopting the gravities and effective temperatures obtained from the preliminary WD solution. We adopted bolometric albedo and gravity brightening coefficients of A = 0.5 and g = 0.32, respectively, values appropriate for stars with convective envelopes. The mass ratio was fixed to the spectroscopic value of 0.9695, and we assumed that there is no light contribution from a third body.

The shape of the I band light curve clearly suggests that the binary is well detached, so mode 2 of the WD code was chosen. To obtain consistency with the spectroscopic solution a grid of photometric solutions was calculated for different values of the eccentricity in the range of values consistent with the spectroscopic data (e.g. 0.034 - 0.042). The following parameters were adjusted: the temperature of the secondary component (T_2), the dimensionless potentials Ω_1, Ω_2, luminosity (L_1), inclination (i), the periastron pasage (ω), eccentricity (e) and the phase displacement (ϕ). The best solution (e.g. with the smallest χ^2) was obtained for e = 0.0395, and the corresponding parameters listed in Table 3. In order to assign realistic errors to these parameters, we computed several grids of models for potentially degenerate parameters and analyzed the corresponding space parameters. The errors derived in this way are also given in Table 3. We also computed a series of models assuming a light contribution from a third body of 2, 4 and 6 %. In each case we found that adding this third light source degraded the quality of our solutions significantly, which confirms our preliminary assumption that there is no third light source in this system.

We conclude that OGLE-051019.64-685812.3 is a completely detached, slightly eccentric system composed of two G4III giants, and therefore is ideal for an accurate distance

determination.

4. Distance Determination

OGLE-051019.64-685812.3 offers us an outstanding opportunity to derive a very accurate distance to the LMC using an empirical surface brightness – color relation (di Benedetto 1998, Groenewegen 2004, Kervella et al. 2004, di Benedetto 2005). We would like to note here, that another calibration given by van Belle (1999) is not accurate enough for our purpose (e.g. about 10 % only, due to the lower accuracy of their measured angular diameters).

Given the long period of the system it was not possible to obtain eclipse light curves in all passbands, and as a result we computed the magnitudes and colors of the individual components by deriving the brightness ratios in different bands from an extrapolation of the I-band solution (e.g. taking into account the information about the temperatures of both components).

Since all available empirical surface brightness-color relations are based on magnitudes calibrated onto the Johnson system, we transformed our photometry to this system using the equations given by Carpenter et al. (2001), and Bessell and Brett (1988). Adopting the reddening law of Schlegel et al. (1998) and a reddening of E(B-V) = 0.146 mag as derived from the OGLE reddening maps, the reddening-free magnitudes and colors of the individual components were calculated. These are listed in Table 3.

The distance in parsecs follows then directly from the Lacy (1977) equation:

$$d(pc) = 1.337 \times 10^{-5} r(km)/\varphi(mas)$$

The linear diameter (r) comes from the analysis of the system while the angular diameter (φ) is derived from the surface brightness-color relations (e.g. $m_0 = S - 5log(\varphi)$, where S is the surface brightness in a given band, and m_0 is the unreddened magnitude of a given star in this band).

Calculating the respective surface brightnesses of the components of OGLE-051019.64-685812.3 from their (V-K) colors and using the calibration of di Benedetto (2005) obtained for a mixed sample of giant and dwarf stars, we obtain distances of (50.4 $\pm$ 1.3) kpc for the primary, and (50.0 $\pm$ 1.4) kpc for the secondary component, corresponding to distance moduli of (18.51 $\pm$ 0.06) mag and (18.49 $\pm$ 0.06) mag, respectively. Very similar results (see Table 2) are obtained using the (V-K) colors and the calibrations of di Benedetto (1998), Groenewegen (2004), Kervella (2004).

It has been shown by Di Benedetto (1998, 2005) that the surface brightness – color relations for late-type dwarf and giant stars are consistent with each other at the level of 1 % . To demonstrate the very low sensitivity of our derived distance value on the adopted surface brightness - color relation, we present in Table 2 the distances of the two components of OGLE-051019.64-685812.3 which we obtain using the surface brightness - color relations based on dwarfs (di Benedetto 1998, Groenewegen 2004, Kervella et al. 2004), giants (di Benedetto 1998, Groenewegen 2004), and a mixed sample of both types of stars (di Benedetto 1998, di Benedetto 2005). The distance results agree extremely well. We adopt for the distance to OGLE-051019.64-685812.3 the value obtained from the most recent di Benedetto (2005) surface brightness-color relation, (18.50 $\pm$ 0.06) mag, because this particular relation is based on a large number of very carefully selected calibrating angular diameter stars.

5. Discussion

In the previous paragraph we decided to use the $V - K$ color to derive the surface brightnesses and distances because the corresponding surface brightness – color relation has the smallest scatter (e.g. Di Benedetto 1998, Kervella et al. 2004, Groenewegen 2004, Di Benedetto 2005). However, the use of other colors, for example $V - I$, leads to very consistent distance results.

The metallicity dependence of the surface brightness is very weak (Thompson et al. 2001, Di Benedetto 1998, Groenewegen 2004). The corrections for metallicity for our system are as small as 0.007 mag for the K-band filter. Therefore we decided to neglect them and assume an additional error of 0.007 mag in the total error budget.

In order to calulate the total uncertainty on our distance determination, the uncertainties on the following quantities were taken into account: K_1 and K_2 (0.5 %), (the absolute dimension is known to 0.5 %), inclination (0.2 %), relative radii (1.2 %), the zero point of the optical (0.6 %) and near infrared (0.8 %) photometries, reddening (0.8 %), and the error associated with the calibration of the surface brightness - color relation (2.0 %). Adding the contributions of these errors on the distance determination to OGLE-051019.64-685812.3 quadratically we obtain a total error of 3 %. We note that any correction for the tilt of the LMC bar with respect to the line of sight is expected to be very small ($<$ 0.01 mag) for our target, due to its position very close to the center of the LMC bar.

Finally, we note that our distance determination is only very weakly dependent on the assumed reddening. This is because the surface brightness - color relation we used is almost parallel to the reddening line. Indeed, if we change the adopted reddening by as much as

0.06 mag (e.g. 3 σ) the distance will change by 1 % only. If we change the reddening law by any reasonable amount (e.g. $R_V = 2.7$) the effect on the distance will be 0.3 %, and therefore negligible.

Since our system is located very close to the barycenter of the LMC, we can assume that its distance represents very closely the distance to the LMC. However, we cannot exclude that the system is located slightly in front or behind the LMC barycenter. We will investigate such a possible depth effect once we have analyzed more late-type eclipsing binaries for which we are currently acquiring the necessary data.

6. Conclusions

We have studied the double-lined late-type LMC eclipsing binary system OGLE-051019.64-685812.3 which we discovered in the database of the OGLE-II Project. From a detailed analysis of its I-band light curve, the radial velocity curves for the two giant components of the system, and near-infrared photometry outside the eclipses we have derived the distance of the system from the $V - K$ surface brightness-color relation for giant stars given by Di Benedetto (2005). We obtain a true distance modulus of 18.50 mag, with a total estimated uncertainty of 3%, or 0.06 mag. This result constitutes a significant improvement on the distance measurements using observations of early-type eclipsing binaries in the LMC (e.g. Guinan et al. 1998, Ribas et al. 2002).

Our derived distance for OGLE-051019.64-685812.3 agrees very well with most recent determinations of the LMC distance from different methods (e.g. Schaefer 2008, Benedict et al. 2007, Fouqué et al. 2007, Guinan et al. 2004).

This is the first of a number of similar eclipsing binary systems we have discovered in the LMC, whose study in forthcoming papers will allow us to reduce the uncertainty on the current distance determination to the LMC from OGLE-051019.64-685812.3. The long orbital periods and faint magnitudes of these systems make the collection of the required photometric and spectroscopic data difficult, but our present results demonstrate the high potential offered by late-type eclipsing binaries to achieve a breakthrough in the reduction of the uncertainty of the distance to the LMC, and to an understanding of the systematics affecting other methods of distance determination.

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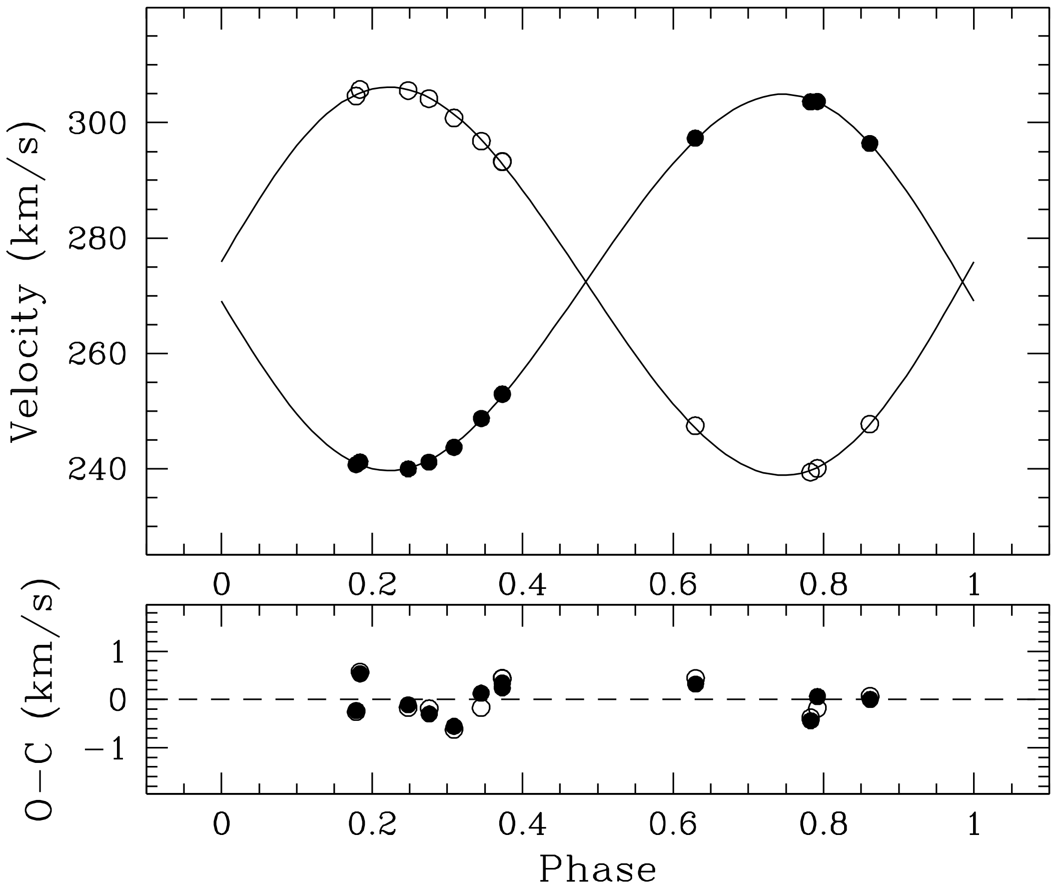

Fig. 1.— Spectroscopic orbit of OGLE-051019.64-685812.3.

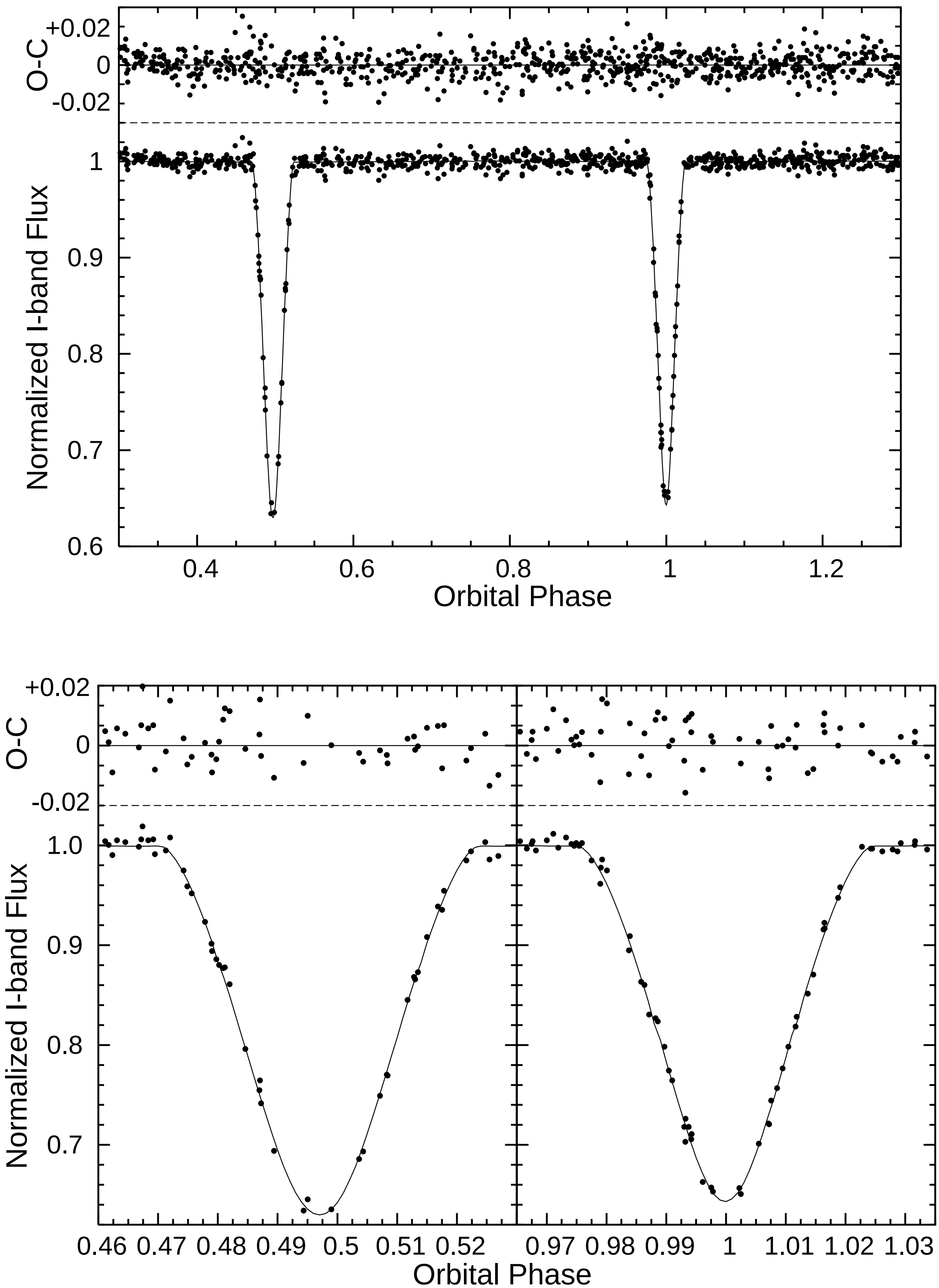

Fig. 2.— Observed I band light curve together with the photometric solution, as obtained from the analysis with the WD code.

Table 1. Radial Velocity Measurements for OGLE-051019.64-685812.3

HJD [days+2400000.0]	V_1 [km/s]	V_2 [km/s]
53989.90267	241.12	304.15
54004.84688	248.68	296.81
54010.79804	252.93	293.26
54010.84238	252.86	293.23
54065.79822	297.33	247.44
54098.63125	303.62	239.35
54183.52206	240.67	304.63
54184.60444	241.15	305.74
54314.91702	303.65	240.04
54329.88495	296.39	247.72
54412.73026	239.94	305.59
54425.78541	243.67	300.83

Table 2. Effective temperature derived from the observed colors. The mean value from all measurements (T_{eff} = 5360 K) was adopted.

T_{eff} [K]	calibration	color
5410	Warthey and Lee (2006)	J-K, V-K, V-I
5320	Ramirez and Melendez (2005)	V-I, V-K
5400	Alonso et al. (1999)	V-K
5300	Di Bededetto (1998)	V-K

Table 3. Astrophysical parameters of OGLE-051019.64-685812.3

	Primary	Secondary
P [days]	214.370 ± 0.008	
i [deg]	88.20 ± 0.10	
a [$R_{\odot}$]	280.8 ± 1.1	
e	0.0395 ± 0.0025	
ω [deg]	96.53 ± 0.46	
φ	0.99850 ± 0.00003	
$q = m_1/m_2$	0.9695 ± 0.0068	
γ [km/s]	272.39 ±0.09	
K [km/s]	32.65 ± 0.14	33.67 ± 0.16
$M/M_{\odot}$	3.29 ± 0.04	3.19 ± 0.04
$R/R_{\odot}$	26.06 ± 0.28	19.76 ± 0.34
$T_{eff}[K]$	5300 ± 100	5450 ± 100
V [mag]	16.738	17.195
I [mag]	15.969	16.466
K [mag]	14.895	15.446
distance [kpc]	50.4 ±1.3	50.0 ±1.4
E(B-V) [mag]	0.146 ± 0.02	
Fe/H	-0.5 dex (assumed)	

Table 4. Distance determinations to OGLE-051019.64-685812.3 based on different calibrations of the surface brightness color relations

d1 [kpc]	d2 [kpc]	luminosity class	color	reference
51.4	50.7	dwarfs	V-K	Di Benedetto (1998)
50.1	49.6	giants	V-K	Di Benedetto (1998)
50.2	49.8	dwarfs + giants	V-K	Di Benedetto (1998)
52.0	51.5	dwarfs + giants	V-I	Di Benedetto (1998)
51.0	50.7	dwarfs	V-K	Kervella et al. (2004)
51.1	50.8	dwarfs	V-K	Groenewegen (2004)
49.8	49.1	giants	V-K	Groenewegen (2004)
50.4	50.0	dwarfs + giants	V-K	Di Benedetto (2005)